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# COMPARATIVE REVIEW OF PHASE CHANGE MATERIALS FOR COOLING DEMAND REDUCTION IN HOT-ARID CLIMATES: INSIGHTS FROM IRAQ AND THE GULF

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***Abstract.*** *In hot and dry countries like Iraq, Saudi Arabia, and the United Arab Emirates, buildings need a lot of cooling, which uses up to 70-80% of all the electricity in homes and offices. This reliance on air conditioning makes energy shortages and environmental problems worse. One way to solve this problem is to use Phase Change Materials (PCMs), like paraffin wax, which can store and release heat to keep indoor temperatures stable and reduce the need for cooling. However, the usual PCM doesn't work well because it can't conduct heat easily. This study examines how PCM can be used in hot and dry climates, focusing on three main types: local paraffin PCM, nano-enhanced PCM, and hybrid PCM systems that work with design strategies that don't use energy. We reviewed over 30 studies published between 2006 and 2025 to compare the results. Using local paraffin PCMs from Iraq can reduce the need for cooling by 20-30%, and it can pay for itself in just 2-3 years. The use of PCMs in buildings can help reduce energy consumption and alleviate the pressure on the energy grid, especially during peak summer months. By incorporating PCMs into building design, architects and engineers can create more sustainable and energy-efficient buildings that are better suited to hot and dry climates. Also, the integration of PCMs with passive design strategies can enhance their effectiveness and provide a more comprehensive solution to the cooling demands in these regions. Overall, the application of PCMs in hot and dry climates offers a promising solution to the challenges posed by extreme cooling demands, and further research and development are needed to fully explore its potential and benefits. The adoption of PCM technology will enable us to create more sustainable and energy-efficient buildings, which not only reduce energy consumption but also provide a better and healthier indoor environment for occupants.*

**Keywords:** *sustainable energy, phase change materials (PCM), solar thermal system, thermal energy, energy storage*

# ПОРІВНЯЛЬНИЙ ОГЛЯД МАТЕРІАЛІВ З ФАЗОВИМ ПЕРЕХОДОМ ДЛЯ ЗНИЖЕННЯ ПОТРЕБИ В ОХОЛОДЖЕННІ В УМОВАХ ЖАРКОГО ТА ПОСУШЛИВОГО КЛІМАТУ: ДОСВІД ІРАКУ ТА КРАЇН ПЕРСЬКОЇ ЗАТОКИ

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***Анотація.*** *У країнах із спекотним, посушливим кліматом, таких як Ірак, Саудівська Аравія та Об’єднані Арабські Емірати, будівлі потребують охолодження, на яке припадає* *до 70–80% загального обсягу споживання електроенергії в житлових і офісних будівлях. Така залежність від систем кондиціювання повітря загострює проблеми дефіциту енергії та негативного впливу на довкілля. Одним із шляхів розв'язання цієї проблеми є використання матеріалів з фазовим переходом (PCM), зокрема парафіну, які здатні акумулювати та віддавати теплоту, підтримуючи стабільну температуру всередині приміщень і зменшуючи потребу в охолодженні. Проте традиційні PCM мають обмежену ефективність через низьку теплопровідність. У цьому дослідженні розглянуто можливість застосування PCM в умовах спекотного й посушливого клімату з акцентом на 3 основні типи: місцеві парафіни PCM, наномодифіковані PCM та гібридні PCM-системи, що включають стратегічні пасивні архітектурні рішення. Нами розглянуто понад 30 наукових праць, опублікованих за період 2006–2025 рр., з метою порівняння отриманих результатів. Встановлено, що використання місцевих парафінових PCM в Іраку дозволяє знизити попит на охолодження на 20–30%, й термін окупності таких рішень становить лише 2–3 роки. Застосування PCM у будівлях сприяє скороченню енергоспоживання та зменшенню навантаження на енергомережі, особливо в періоди пікового літнього попиту. Інтеграція PCM у проєктування будівель дозволяє архітекторам та інженерам створювати більш стійкі й енергоефективні будівлі, краще пристосовані до експлуатації в умовах спекотного, посушливого клімату. Крім того, застосування матеріалів з фазовим переходом (PCM) у поєднанні з пасивними архітектурними рішеннями підвищує ефективність їх використання та забезпечує комплексніший підхід до задоволення потреб в охолодженні в таких регіонах. Загалом застосування PCM у спекотних та посушливих кліматичних зонах є перспективним рішенням для подолання проблем, пов'язаних із високим попитом на охолодження. З метою повнішого розкриття потенціалу та переваг цієї технології необхідні подальші дослідження. Впровадження технологій PCM сприятиме будівництву більш сталих та енергоефективних будівель, які не лише споживають менше енергії, а й забезпечують комфортніші та здоровіші умови для користувачів.*

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***Ключові слова:*** *стала енергетика, матеріали з фазовим переходом (PCM), сонячна теплова система, теплова енергія, акумулювання енергії.*

**Introduction.** The building sector is one of the largest energy consumers worldwide, accounting for about 40% of the total energy consumption. The corresponding amount of greenhouse gases emitted from the building sector poses a significant challenge, especially with respect to cooling demand in hot-arid climates. Countries such as Iraq, Saudi Arabia, and the United Arab Emirates (UAE) experience extremely hot summers with average temperatures of 45 °C and above and high solar irradiation during long cooling seasons [2][3]. Air-conditioning systems, mostly mechanical, are widely used in residential and commercial buildings in these countries. The corresponding share of cooling in the total energy consumption of buildings is between 65–80%, which puts an extreme strain on the power grids of these countries and causes environmental problems, since most of the electricity is generated from fossil fuels in the Middle East.

***Energy Challenges in Hot-Arid Climates.*** The urbanization trend in the Gulf and the Middle East region is further driving the cooling demand. In Saudi Arabia, for instance, the electricity consumption from buildings represents some 50% of the total electricity consumption. More than 70% of this consumption is attributed to the cool air used in homes. [2]. Climate change will influence future cooling energy demand in the UAE. According to "Business-as-usual" future energy scenario, projected increase of cooling energy demand by 2050 will reach 22% and by 2080 it will reach 40%. Similar challenges exist in cooling energy demand in Iraq despite the abundance of oil resources.

[5]. Statistics recently published highlight a great challenge for the world: the need for innovative ways to cool while saving energy.

***Phase Change Materials (PCM) as a Solution.*** Phase Change Materials (PCMs) have become an attractive solution for building thermal energy storage. In order to utilize the latent heat of a PCM, which undergoes a solid-liquid phase change, large amounts of energy can be stored and also be released again nearly at constant temperature. This allows to reduce temperature swings inside a building and to shift air conditioning peak loads to off-peak hours. [1]. Paraffin wax in particular has received a lot of attention due to its favorable physical and chemical properties. It is chemically stable, non-corrosive, readily available as a by-product from the petroleum refining process, and has a melt point within a comfortable range for human use (20-45 °C).

[6]. In Iraq, paraffin wax produced locally was used as a PCM in roof structures, the results indicated significant reduction of indoor heat flux as well as savings in electricity

as compared with commercial PCMs. [5]. Similarly, Chaichan et al. [7] Integrating paraffin PCM into a solar distillation system was shown to increase the productivity of such systems by almost 783%. This will enable further uses of the energy.

***Limitations of Conventional PCM.*** While conventional paraffin PCM offer many advantages to the energy storage, the poor thermal conductivity of paraffin PCM (about 0.2 W/m·K) significantly restricts the charging/discharging rate and efficiency for building applications. [8]. Due to self-insulating effect of emulsion, melting and heat transfer are non-uniform. Besides, leakage, phase separation and instability of emulsion during long-term storage are serious problems for the large-scale application of the emulsion. [1]. To overcome the above problems, many modifications have been explored by the researchers, including encapsulation, shape stabilization and also by adding high electrical conductivity materials such as metals, graphite and nanoparticles [6].

***Nano-Enhanced PCM.*** Nano-enhanced PCMs are a class of PCMs currently under development to improve the thermal properties of PCMs. By adding various types of nano-particles, such as $Al_2O_3$, $TiO_2$, and graphene to PCMs, the thermal conductivity can be improved by 40–60% or more. In addition to increased thermal conductivity, the charging time of PCMs can be greatly reduced resulting in a very efficient system [9][10]. For example, Chaichan et al. [9] The addition of 3% $Al_2O_3$ to paraffin reduced the charging time from 13 min to 5 min. Li et al. [10]. We also demonstrated that graphene-based composites achieve superior electrical conductivity and stability at very low loadings. This makes nano-enhanced PCMs a promising means to adapt PCMs for hot-arid climate zones by significantly increasing their performance at very low loading.

***Passive and Hybrid Cooling Strategies.*** Building insulation materials with PCM can be effective in conjunction with passive and hybrid cooling strategies. In addition to improving the thermal properties of building materials, PCM can be integrated into passive and hybrid cooling systems to enhance their cooling potential. Shading, optimized glazing and insulation can reduce cooling loads in typical Saudi villas by 30–68% [2]. Hybrid systems such as radiant cooling ceilings with integrated PCM panels in the ceiling slab can save 15–27% more energy than conventional systems [11][12]. Capillary tube PCM systems, which combine hydronic radiant cooling with PCM storage, further enhance thermal buffering [13]. Combining PCM with appropriate architectural and engineering solutions to maximize performance.

**Objective of the work.** Worldwide many scientific investigations have been conducted on PCM (Latent Heat Storage) and nano-enhanced PCM in recent years. However, the majority of them were categorized as “worldwide” without any reference to the application in the Gulf region or in Iraq. In addition, the majority of experimental and numerical comparisons that have been carried out so far were of a short-term nature and did not permit any statement with respect to the long-term durability of PCM as well as to cost-effectiveness and user comfort of buildings equipped with PCM. Various strategies can be thought of in order to use PCM in buildings. The usage of local paraffin PCM, the usage of nano-enhanced PCMs as well as the usage of hybrid PCM systems represent possible strategies. In the present paper a comprehensive review on the application of PCM in hot-arid climates will be given and a special focus will be put on the application of PCM in the Gulf region and in Iraq.

1. Compare local paraffin PCM with commercial PCMs and with nano-enhanced PCMs.
2. What is the potential of integration of PCM with passive cooling as well as with hybrid cooling systems.
3. Compare PCM applications in terms of energy efficiency, cooling demand and payback period.
4. Problems, gaps in knowledge and future trends for PCM applications in Gulf region and in Iraq.

**Background and Literature Review**

***Thermal Energy Storage in Buildings.*** Using thermal energy storage (TES) can reduce the specific energy consumption of a building. For many years, sensible heat storage by means of hot water, concrete or rock was the most common application of TES. However, for light-weight buildings the large amount of material required for storing a considerable amount of heat is not very suitable. The application of latent heat thermal energy storage (LHTES) by means of PCMs is far superior in this respect, as it is able to store 5–14 times as much heat in the same volume as sensible storage. [1]. PCMs are able to store and release heat while changing from a solid to a liquid and back again. Such PCMs maintain nearly constant temperature and thus can be used for climate conditioning. Ref. Soussi et al. [15] In this paper a general view on the present methods for greenhouse climate control is given. By means of several examples for the application of integrated cooling methods (ventilation, evaporative cooling, desiccant cooling) the respective methods are described. The possibilities and limits of the single methods are compared with each other. Suggestions are given on how to combine ndividual methods in an efficient way to reduce water and energy consumption in arid climates. Unlike Mohammed et al. [16] and Thaib et al. [17], in this work, an experimental study on the cooling of PV panels using PCMs, like beeswax and paraffin, has been performed. The results have shown the potential of temperature decrease of the PV panels and an increase in the efficiency of electric energy, which is produced by the PV panels. It has also been shown that the results of this study are time dependent and this is caused by the latent heat of the PCM used in this study. Contrary to the other studies, where cooling is investigated at the component level, like PV module, etc., in this work, cooling at the system level, like PV panel, is investigated by Tembhare et al. [18] This discussion is further extended to the application of enhanced heat transfer nanofluids to both solar thermal and PV systems. These are challenges with the stability of the nanofluid and the scalability of its use in systems. Transport of nanofluid models are discussed by Siddiqui et al. [19] A comprehensive review of multi-physics PV models. These models describe the thermal, optical and electrical behavior of PV modules. They are very useful to enhance the accuracy of the power output prediction of PV modules. In the building sector, these models can support experimental investigations with theoretical analysis. Ref. Al-Yasiri and Szabó [20], Saxena et al. [21], and Khdair and Abu Rumman [22] explore PCM integration within building envelopes, demonstrating significant improvements in indoor thermal stability and energy savings, particularly when combined with insulation or natural ventilation strategies. Similarly, Solgi et al. [23] A number of additional recent references on PCMs and night cooling are summarized with the conclusion that, in many cases, climate will trump. Zhang and Lee. [24] This paper takes a step from policy to economic optimization of the increase of photovoltaic systems by means of feed-in tariffs. The technical views on cooling and PCMs for improving the energy efficiency of photovoltaic systems in hot and arid climates are complemented by a techno-economic view on the use of these components. While experimental as well as simulation studies clearly can show the advantages of using PCMs as well as of advanced cooling systems for the thermal performance of photovoltaic systems, the efficiency of these systems strongly depends on the special application. Therefore, an integration in a complete system design, modeling as well as in policy frameworks is necessary.

***Classification of PCMs.*** PCMs are broadly classified into three categories: organic, inorganic, and eutectic [7].

- Organic PCMs are paraffin waxes and fatty acids. Of these organic PCMs the paraffin waxes are the most commonly used PCMs. This is due to their good chemical stability, their congruent melting behavior and their availability (as a petroleum byproduct). Pure paraffin wax is made up of straight-chain n-alkanes ($C_nH_{2n+2}$) and has a melting point of 20–45 °C. This makes the paraffin wax very suitable for use in building applications. [7].
- Inorganic PCMs are typically made from salt hydrates and molten salts. They have a high thermal conductivity and high density. However, several drawbacks, such as supercooling, phase segregation and corrosion, exist for many inorganic PCMs. [1].
- Eutectic PCMs are a physical mixture of two or more components having a designed melting point. Within these mixtures, no liquid/solid phase separation occurs upon melting or solidification.

***Incorporation Methods.*** Several methods have been developed to integrate PCM into building structures [5][6]:

1. The PCM can be mixed into building materials (gypsum plaster, new or in-use concrete). This is the simplest method of integration; however, it is prone to leakage and incompatibility problems.
2. Immersion: A liquid PCM is cast around the component in question so that it is completely covered by the PCM liquid. The PCM will fill all pores of the component. As with incorporation into building materials, the major problem of leakage also occurs in immersed components and restricts long-term use.
3. Macro-encapsulation: Building components are immersed in a liquid PCM. After solidification of the PCM (by cooling down to the solidification temperature) the liquid PCM fills the pores of the component in question. Like with direct incorporation, the risk of leakage restricts the long-term use of such components. Therefore, macro-encapsulated PCMs are used in a variety of modules and can easily be integrated into buildings.
4. Micro-encapsulation: In micro-encapsulated PCMs the PCMs are surrounded by polymer shells. The microcapsules can be mixed into paints or into new and old plaster or into fibers in order to create new PCM-textiles.
5. Shape-stabilized composites: By mixing PCM with polymers or with porous matrices, PCM-based shape-stabilized composites are produced, which have mechanical stability and no leakage.

Different methods can be used for the integration of PCM into building components. The methods have their specific advantages and disadvantages. Above all, the low thermal conductivity of PCMs is problematic for their use in buildings.

***Limitations of Conventional PCMs.*** Although conventional paraffin PCMs are inexpensive and have a high heat storage capacity, their low thermal conductivity (about 0.2 W/m·K) prevents fast charge/discharge of the thermal storage material as well as a uniform melting and solidification. [8]. The self-insulating behavior of dielectric cooling insulating materials greatly hinders the application efficiency of buildings in changing climatic circumstances. The large scale application of such insulating material has a number of constraints, such as leakage, segregation of the phases and long term stability. [1]. Addressing these limitations has become a major focus of PCM research.

***Nano-Enhanced PCMs.*** By embedding nanoparticles in the PCM, a significant enhancement in thermal conductivity can be achieved, which in turn could improve the charging time and the system's stability. $Al_2O_3$, $TiO_2$ and graphene have been tested as potential candidates for this aim. [9][10].

- $Al_2O_3$-enhanced PCM: Chaichan et al. [9] reported that adding 3% $Al_2O_3$ to paraffin improved conductivity by 60% and reduced charging time from 13 minutes to 5 minutes.
- $TiO_2$-enhanced PCM: Li et al. [10] showed that $TiO_2$ nanoparticles improved conductivity by ~40% at very low concentrations (0.01%), offering cost-effective enhancement.
- Graphene-enhanced PCM: Graphene composites demonstrated superior stability and conductivity, making them promising for long-term applications [14].

These findings suggest that nano-enhanced PCM can overcome the fundamental limitations of paraffin, enabling its use in extreme climates.

***Passive Cooling Strategies.*** Passive design strategies can still play a significant role in buildings found in hot-arid climates. Strategies including shading, optimum glazing and insulation can provide up to 30–68% reduction in cooling demand for typical Saudi villas. The traditional wind tower used in Gulf architecture can further reduce internal temperatures by up to 13–16% by enabling natural ventilation. Strategies for roof treatments can also reduce heat gain to the building. Studies conducted in the capital city of Riyadh have found that by using such strategies, cooling energy consumption can be reduced by 12–33%. [2]. These strategies, while effective, are often insufficient alone during peak summer conditions, necessitating integration with PCM.

***Hybrid PCM Systems.*** Hybrid systems combine PCM with active cooling technologies.

- Radiant PCM ceilings: Bogatu et al. [11] In a study of macro-encapsulated PCM panels with integrated pipes the authors determined the cooling capacity of such a system. The results of the experiments showed cooling capacities of 5–27 W/m² to reduce peak loads and to ensure a comfortable user temperature.
- Capillary tube PCM systems: Jobli et al. [13] integrated PCM with hydronic radiant cooling, achieving prolonged thermal buffering and energy savings of 20–35%.
- Comparative studies: Skovajsa et al. [12]. A 27% cooling demand reduction was achieved by integrating PCM in conventional cooling systems.

The potential for combining PCM (Passive) and active systems in hot-arid climates is huge and can be used in a synergistic way.

**Methodology**

***Scope of the Review.*** Title of above work: PCMs and nano-enhanced PCM in building design for cooling demand reduction of buildings in hot-arid climates: A review. A number of globally reviewed studies conducted between 2015 and 2025 were mainly systematically reviewed articles (SRA) published in reputable journals. A number of globally reviewed studies were from Iraq, Saudi Arabia and UAE therefore globally applicable.

The review emphasizes three categories of PCM applications:

1. Local paraffin PCM – using local paraffin PCM, such as indigenous paraffin wax which is available in Iraq and other countries.
2. Nano-enhanced PCM – PCM doped with nano-particles (e.g. $Al_2O_3$, $TiO_2$, graphene etc.) to enhance the thermal conductivity of PCM.

Hybrid PCM systems are designed to incorporate phase change materials into various building elements, such as walls, floors, and ceilings. Most of the research focuses on using these systems for cooling purposes, either passively or actively. When it comes to radiant cooling using PCMs, different terms are used to describe the process, including ceiling cooling and capillary tube cooling systems. In many cases, PCMs used in building applications are combined with shading devices to enhance their effectiveness. By integrating PCMs into building design, it's possible to create more efficient and sustainable cooling systems. The use of PCMs in building elements can help regulate temperatures, reducing the need for traditional cooling methods and minimizing energy consumption. Additionally, combining PCMs with shading devices can further improve their performance, allowing for more precise control over temperature fluctuations. Overall, hybrid PCM systems offer a promising solution for building designers and engineers looking to create more energy-efficient and environmentally friendly structures.

***Data Sources and Selection Criteria.*** This section outlines the review of current knowledge. The databases searched for relevant information were ScienceDirect, Elsevier, MDPI, Taylor & Francis and IEEE Xplore online databases. These online databases were selected as the primary databases as they contain a vast amount of up-to-date information relevant to this research. In order to gather sufficient knowledge from the above databases, a number of search terms were utilized. The search terms ‘application of advanced materials in construction’ and ‘improvement of material properties by using nanoparticles to modify/ enhance their properties’ were used individually and in combination to identify the most relevant studies. These studies relate to innovative building materials and sustainable building cooling techniques.

The selection criteria were as follows:

- Inclusion criteria:
- Studies that present PCM (Phase Change Material) applications in building/thermal systems.
- The research was conducted in hot-arid climates or in Iraq and the Gulf region.
- Studies that present PCM (Phase Change Material) applications in buildings or in thermal systems.
- The research was conducted in hot-arid climates or in Iraq and the Gulf region.
- Experimental, numerical or computer simulation studies with quantitative results (cooling down loads, energy saving, increase of thermal conductivity, etc.) on applications of PCM in buildings or in thermal systems.
- Exclusion criteria:
- Studies outside the 2015–2025 timeframe.
- Papers outside the 2015–2025 time frame. Use of heat in very cold climates (other than hot-arid climates of the desert in Iraq and the Gulf region).
- Papers lacking quantitative data or peer-review vali-dation.

***Comparative Framework.*** The selected studies are categorized, compared and evaluated by a fixed framework in order to evaluate and assess their results.

- Reduction of the cooling load in %: how much the cooling demand is reduced by compared to the reference case.
- Energy savings (%) – the energy saving in electricity consumption due to the PCM incorporation.
- Thermal conductivity improvement (%) : The increase in thermal conductivity of the PCM by the nano-additives.
- Payback period (years): This indicator characterizes the economic expediency of a system by comparing the specific investment with the specific savings.
- Comfort metrics (indoor temperature stability and peak demand reduction, etc.) that help assess indoor thermal comfort.

The framework of analysis also enables comparison between PCM-based strategies and other PCM studies based on Iraqi paraffin as the PCM, with other nano-enhanced PCM studies around the world, and also between hybrid cooling systems and passive cooling systems.

***Analytical Approach.*** Selected data from the reviewed studies were organized in tables and charts comparing the studies' results. The tables include indicators for the compared PCMs and strategies, along with corresponding references to enable a comparison. Statistical trends could be identified in some cases. However, since the used methodologies for the experimental investigations strongly differ regarding test stand, climate and PCM composition, the results were synthesized in a mainly qualitative manner and enable a comprehensive and region-specific analysis of the investigated PCMs and strategies for upgrading building components.

The review of existing studies on building components is carried out by means of a structured methodology that enables to collect and compare a wide set of information, thus providing a complete overview of the state of the art and, at the same time, enabling to highlight the strengths and the weaknesses of different approaches, in order to set up a comparative analysis and a discussion that is consistent and complete.

**Comparative Analysis**

***Framework for Comparison.*** In this paper, a number of studies on the use of various indicators for assessing the performance of PCM in hot-arid climates were summarized.

- Cooling load reduction (%)
- Energy savings (%)
- Thermal conductivity improvement (%)
- Payback period (years)

• Comfort metrics (temperature stabilization, peak load reduction) Sahip et al.[25]. An applied experimental work has been conducted to enhance the performance of solar still by introducing a novel concept of rotating cotton mesh fabric inside the distillation chamber. The experiments have been conducted to investigate the performance of a novel setup under Kirkuk conditions, and results have been used to investigate the effect of mechanical augmentation of the evaporation surface on thermal efficiency and water productivity. The results showed that by incorporating cotton mesh fabric into the distillation chamber and mechanically revolutionising it within the still, the highest thermal efficiency and water productivity have been achieved. The novel setup primarily focused to enhance heat distribution and evaporation kinetics rather than storing energy. This paper is in contrast with the review article titled "Review of solar stills research" by Hicham Johra and Per Heiselberg. [26]. From an indoor perspective, the thermal dynamics of buildings are affected a great deal by internal thermal mass, primarily furniture. The work presented focuses on the energy performance of a building from this perspective and outlines the limitations of conventional models that do not account for mass. The paper also describes the use of Phase Change Materials (PCM) in enhancing the thermal mass of a building to increase its energy flexibility. Related work by Guruprasad Alva et al. [27]. A general overview of TES systems is given. These are classified into sensible, latent and thermochemical storage. Their relevant material properties, storage system configurations and a wide variety of applications, e.g. by means of solar energy as well as for industrial purposes, are described. Earlier work of the authors Vineet Veer Tyagi and D. Buddhi is referred to. [28]. The reviewed PCM applications integrated into building envelopes and passive heating/cooling systems were systematically assessed in terms of their effectiveness to reduce the buildings' energy demands. It is observed that, while Sahip et al. focused in their study on enhancing the real-time use of thermal energy generated in solar desalination systems through mechanical means, other studies concentrated on storing and regulating thermal energy using advanced materials. This framework (see figure 1) enables us to review locally applied paraffin PCM in Iraq, nano-enhanced PCM as well as hybrid PCM systems on the one hand, and passive building design strategies in Saudi Arabia and the UAE on the other hand.

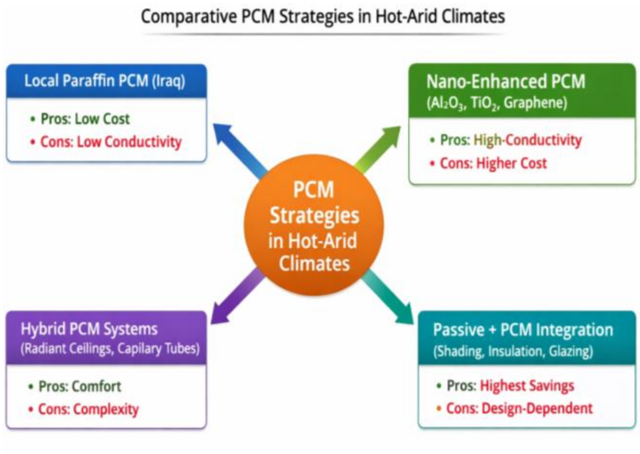


*Fig. 1. Schematic comparison of PCM strategies in hot-arid climates*

**Discussion of Comparative Findings**

***Iraqi Paraffin PCMs.*** Local paraffin wax has proven effective in reducing cooling loads by 20–30% when integrated into roof structures [5]. Liquid or solid salt storage of heat is a cheap method which is already well established within the oil industry in Iraq. Due to their low thermal conductivity (approximately 0.2 W/m·K), they are, however, not of much use. Nevertheless, they have a quick payback period of 2 – 3 years and might be of interest for single houses to store heat and to save energy.

***Nano-Enhanced PCMs.*** Nano-additives significantly improve PCM performance. Chaichan et al. [9] demonstrated that $Al_2O_3$ nanoparticles increased conductivity by 60% and reduced charging time by more than half. Li et al. [10] To increase the conductivity of the system whilst retaining cost and stability, our investigations suggested that the best option would be to use a combination of $TiO_2$ and graphene composites. Such a system would offer a 40-50% increase in conductivity with associated reductions in cooling demand of 35-60% and associated energy savings of 25-40%. However, it would take 3-5 years to recover the increased material costs.

***Hybrid PCM Systems.*** Hybrid systems integrating PCM with radiant cooling or capillary tubes provide enhanced thermal buffering. Bogatu et al. [11] reported that radiant PCM ceilings reduced cooling demand by 27% and maintained comfort for 83% of occupied hours. Jobli et al. [13]. Capillary tube PCM systems offer a means to decrease the cooling demand by 30–40% and extend the thermal storage period. Such systems can also be used for retrofitting of lightweight buildings, but have a more complex installation than other PCM systems.

***Passive + PCM Synergy.*** Passive strategies such as shading, insulation, and optimized glazing remain highly effective. Rodrigues et al. [2] A study on Saudi villas, which included passive design measures and the use of Phase Change Materials (PCM), found a maximum reduction of cooling demand of 68%. It is found that PCM are very effective when used as an integral component of the building's overall design rather than as an add-on to improve the performance of a material.

***Regional Climate Adaptation.*** Shanks & Nezamifar [3] The expected increase in cooling demand due to climate change up to 22% by 2050 and up to 40% by 2080 in the UAE requires immediate action to retrofit buildings with improved glazing and insulation in order to reduce the cooling demand by 10-35%. PCM and passive cooling measures need to be implemented in order to increase the climate change resilience of buildings in the Gulf region. Action needs to be taken soon.

**Results and Discussion**

***Performance of Local Paraffin PCM.*** Several studies conducted in Iraq are aimed at assessing the potential of using local paraffin wax in building envelopes for cooling load reduction of buildings. Akeiber et al. [5]. Incorporation of paraffin PCM into the roof of a building under study caused a reduction of indoor temperature fluctuations by 20–30% and energy savings of 15–25% in cooling mode. These results are very important for cooling-dominated city of Baghdad and other similar cities, where the average summer maximum temperature exceeds 45 °C. The results are economically feasible with payback period of 2–3 years, thus locally-manufactured PCM can be considered as a cost-effective building retrofit measure for residential buildings in Baghdad. Since the thermal conductivity of paraffin PCM used is low (approximately 0.2 W/m·K), it cannot absorb or release heat quickly. The results of the present study have been compared with the results of the study conducted by A.K. Pandey et al. [29]. Our examples illustrate the diversity of applications for PCMs for solar thermal, PV or building systems. As energy that is stored by PCMs during sunshine can be released again during periods of no sunshine, thus covering the difference between energy supply and demand, they link up with the system-oriented approach of Sheng Zhang et al. [30], These researchers attempt to combine renewable energy systems with thermal and electrical storage in order to create highly efficient near-zero energy buildings. Such buildings function well under changing weather circumstances.

There are a number of papers on using solar in building applications, such as the recent paper by Huakeer Wang et al. [31]. The results confirm that PCM wallboards are able to provide stabilization of the indoor temperature and of the energy consumption. The melting temperatures of optimal PCM's are close to the temperature range which is perceived to be comfortable by man (22–26 °C). In addition, Kai Jiao et al. [32]. A state-of-the-art review of PCM integrated building envelopes, focusing on how the latest encapsulation strategies and hybrid systems can enhance thermal mass, reduce peak demands on cooling and heating systems and improve occupant comfort. The review highlights the challenges to the material's successful use of cost, safety and performance. [33]. Image segmentation has recently been the focus of much research, but also gives rise to a number of problems that currently are not adequately addressed by available solutions. First and foremost, the many different experimental setups and models employed, lead to a number of serious differences between the results achieved by different methods, which can not at present be compared. Therefore, evaluation frameworks must be standardized. Recent developments also extend toward sustainability and material innovation. Galina Simonsen et al. [34] Bio-based PCMs represent an alternative to standard materials that provide high thermal storage while addressing on material level lifecycle/sustainability related issues. More on that by Zakaria Ouaouja et al..[35], The article in front of us is a paper on applications of PCM for cold thermal energy storage systems mainly for refrigerating and for cold-chain-logistics. The paper quantitatively explains efficiency promotion and environmental benefits. It is followed by an article on material engineering by Teppei Oya and his team.[36]. Leverage the vastly underdeveloped market for composite PCMs embedded in porous metals to create a material with dramatically increased thermal conductivity that can facilitate faster heat transfer, a major limitation for traditional PCMs.

***Impact of Nano-Enhanced PCMs.*** Nano-enhanced PCMs addresses the conductivity limitation of conventional paraffin. Chaichan et al. [7] demonstrated that adding 3% $Al_2O_3$ nanoparticles improved conductivity by 60% and reduced charging time from 13 minutes to 5 minutes. Li et al. [10] Most recent studies used TiO2 and graphene to increase the thermal conductivity of a base fluid at very low loadings, and reported a large increase in thermal conductivity of 40–50%. Corresponding cooling load reductions, as well as reductions in cooling energy and in total energy, were in the ranges of 35–60% and 25–40%, respectively. Although the percentage increase in thermal conductivity is very large, long payback periods of 3–5 years are expected due to the high cost of the nanoparticles. Of greater importance, the long-term thermal conductivity and efficiency of the cooler were also found to be increased. Nano-PCMs make it a promising solution for climates with extreme diurnal temperature variations, such as Iraq and the Gulf.

***Hybrid PCM Systems.*** Hybrid systems integrating PCMs with active cooling technologies provide additional resilience. Bogatu et al. [11] showed that radiant PCM ceilings achieved cooling power between 5–27 W/m², reducing peak loads and maintaining comfort for 83% of occupied hours. Jobli et al. [13] demonstrated that capillary tube PCM systems prolonged thermal buffering, thereby reducing cooling demand by 30–40%. These systems are particularly attractive for lightweight buildings, where conventional thermal mass is insufficient. However, installation complexity and higher initial costs may limit widespread adoption without policy incentives. Pushpendra Kumar Singh Rathore et al. [37] demonstrate that integrating PCMs into solar thermal technologies—such as solar water heaters, desalination systems, and solar dryers—significantly improves efficiency, productivity, and energy utilization while also contributing to $CO_2$ emission reduction. This perspective aligns with earlier comparative work by Shimin Wang et al. [38], Latent heat storage using PCM's (Phase Change Materials) has a much higher energy density than sensible heat storage systems. Thus, they are much more compact and very efficient for storing heat. Therefore, PCM's are very suitable for long-term storage in CSP (Concentrated Solar Power) systems. Tung-Chai Ling and Chi-Sun Poon [39] One field of application for the PCMs are concretes. By introducing PCMs into concrete, the thermal properties of the building material can be improved. The stored heat of the concrete is released during the solidification of the concrete and the latent heat of the PCMs is used for the phase change. Up to now, the mechanical characteristics of the PCMs have not been satisfactory. However, by a proper choice of the PCM and the integration into the concrete,the disadvantages of the PCMs can be mitigated. The advantages and disadvantages of the use of PCMs in different fields of application are of the same order of magnitude as shown in the review of the state of art of the PCM applications. Thus, thermal, constructive and economic disadvantages of the use of PCMs in buildings are of the same order of magnitude.

| Strategy / Study | Location | Cooling Load Reduction (%) | Energy Savings (%) | Thermal Conductivity Improvement (%) | Payback Period (Years) | References |
|---|---|---|---|---|---|---|
| Iraqi Paraffin PCM (Akeiber, 2016) | Baghdad, Iraq | 20–30 | 15–25 | Baseline (0.2 W/m·K) | 2–3 | [5] |
| Solar Distillation PCM (Chaichan et al. 2016) | Najaf, Iraq | Productivity ↑ 783% | N/A | Baseline paraffin | <2 | [7] |
| Nano-PCM $Al_2O_3$ (Chaichan et al. 2017) | Iraq (Lab Study) | 35–60 | 25–40 | +60% (3% $Al_2O_3$) | 3–4 | [9] |
| Nano-PCM $TiO_2$ (Li et al. 2020) | China (Lab Study) | 30–40 | 20–35 | +40% (0.01% $TiO_2$) | 3–4 | [10] |
| Nano-PCM Graphene (Li et al. 2025) | China (Lab Study) | 40–50 | 30–40 | +50% (low wt%) | 4–5 | [14] |
| Radiant PCM Ceiling (Bogatu et al. 2021) | Denmark (Exp.) | 27 | 15 | N/A | 4–5 | [11] |
| Capillary Tube PCM (Jobli et al. 2019) | UK (Exp.) | 30–40 | 20–35 | N/A | 3–4 | [13] |
| Hybrid PCM + Passive (Rodrigues et al. 2025) | Saudi Arabia | 68 | 40–50 | N/A | 2–3 | [2] |
| Passive Shading + Insulation (Saudi) | Riyadh, Saudi | 30–37 | 20–30 | N/A | 2–3 | [2] |
| Climate Change Retrofit (Shanks & Nezamifar 2013) | Dubai, UAE | Demand ↑ 22–40% (future) | Retrofit savings 10–35% | N/A | 3–5 | [3] |

***Passive + PCM Synergy***. Passive strategies remain essential in hot-arid climates. Rodrigues et al. [2] previously showed in their study that integrated the passive building features with latent cooling using PCMs showed 68% energy saving in cooling for typical Saudi villas. Although the study showed that PCM's alone are not sufficient to cool down the building, they can be effectively integrated with building design. For under-insulated building stock of a country like Iraq, integration of PCM's with passive retrofits can lead to substantial energy savings as well as a high level of user comfort.

***Regional Climate Adaptation.*** Climate change projections underscore the urgency of adopting PCM strategies. Shanks & Nezamifar [3] Cooling demand in the UAE is expected to increase by 22% by 2050 and by 40% by 2080 (recent report). A building retrofit using improved glazing and insulation can reduce the increase in cooling demand by 10–35%. However, such a retrofit does not add any extra thermal mass buffering capacity, and therefore it is vastly inferior to a building retrofit using PCM. In countries such as Iraq, where power cut-offs occur frequently during peak summer hours, using PCMs in buildings can assist in reducing mechanical cooling load and help the building to tackle climate variability.

***Comparative Insights.*** The comparative analysis reveals several key insights:

- PCMs that were developed within the GCC have low thermal conductivity and are cost-effective.
- PCMs with nano-structure have higher thermal conductivity than conventional PCMs and are more efficient for heat transfer. However, the cost of these PCMs is very high and not suitable for usage.
- Hybrid PCM systems for users have big potential, since they are cost-effective for building operation and cost saving. However, the systems under investigation have too complex structures and are therefore not suitable as retrofits for existing buildings.
- For the above-mentioned considered systems, the highest energy saving is achieved by passive systems in combination with PCMs.

Step by step Recommendations for GCC and Iraq: 1- Local PCM can be used for building retrofitting by introducing PCM into building external components such as the roof and wall layers. 2- Nano- enhanced PCM can be used in future high-performance buildings under design and construction. 3- PCM should be used in passive building design for future new building designs under design and construction.

The recent review by Laura Vallese et al. [40] This article offers one of the most comprehensive contributions on TES by first of all thoroughly classifying the existing TES technologies (sensible, latent and thermochemical) and then introducing a structured, open-access database which allows for a comparison of the TES systems on the basis of efficiency, costs, applicable temperature and MTRL. The article thus goes beyond typical reviews on TES and really offers a powerful decision support tool for the users. It closes a significant gap in the TES research community by providing, for the first time, a platform that allows for easy access to TES information in a structured and comparable way. This will facilitate the wider application of TES in renewable energy and HVAC. In contrast, the experimental study by Suresh and Saini [41] into the storage systems during discharge shows that latent heat storage systems clearly are more efficient than sensible heat storage systems. The storage systems filled with PCMs, in contrast to the storage systems without PCMs, were able to extend the discharge time by 104 % and to recharge four times the energy. These results are in good agreement with the large-scale review of PCM-based systems by Vallese et al. [40].

From a broader environmental and application perspective, Pieter de Wilde and David Coley [42] emphasize the growing importance of adapting building energy systems to climate change, highlighting the need for resilient designs capable of handling dynamic environmental conditions. TES technologies, particularly those involving PCMs, are implicitly positioned as key enablers for such resilience due to their capacity to buffer thermal fluctuations [43-45][48].

At the material innovation level, Zhang Tao et al. [49] In this contribution, a new approach to extend PCM (Phase Change Materials) applications by using a novel, polypyrrole-coated carbon nanotube-aerogel as the PCM-matrix, which is filled with paraffin wax has been developed. The resulting composite PCM features high thermal conductivity as well as good thermal cycling stability. So the fundamental restrictions of conventional PCMs with respect to their low thermal conductivity have been removed. The presented work also enables multi-functional energy conversion, i.e. by means of solar as well as of electro-thermal energy. Thus, this contribution finally closes the gap between energy storage and energy harvesting.

**Challenges and Research Gaps**

***Technical Challenges.*** Despite the promising results of PCM and nano-enhanced PCM systems, several technical issues remain unresolved:

- Thermal Stability: PCM leakage, phase segregation, and thermal degradation over time reduce reliability and long-term performance [1].
- Nano-PCM Durability: Stabilizing nanoparticles within PCM matrices over extended cycles remains difficult, as agglomeration can reduce conductivity and uniformity [14].
- Low Conductivity: Even with nano-additives, achieving uniform heat distribution throughout large PCM volumes is challenging, particularly in thick building components [8].
- Integration Complexity: Embedding PCM into walls, roofs, and floors requires careful design to prevent thermal bridging and ensure effective heat exchange.

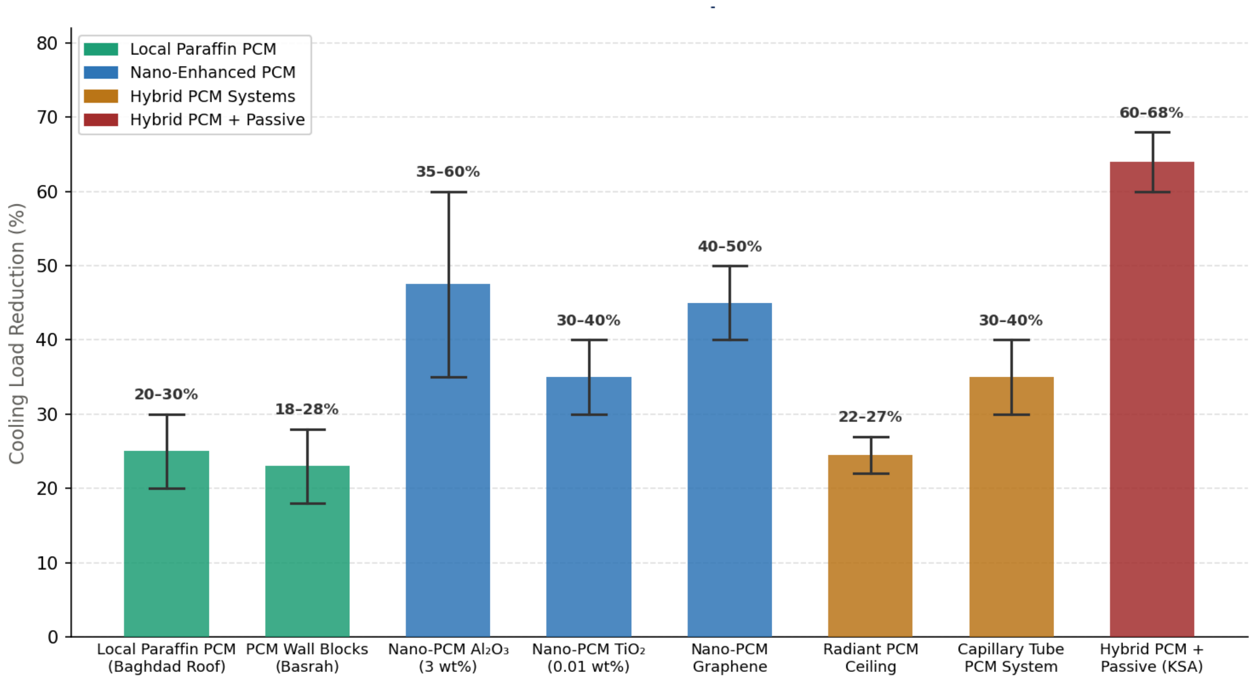


*Fig. 2. Cooling Load Reduction (%) by PCM Strategy. Error bars show reported min–max ranges. The wide ranges for nano-PCM strategies (e.g., $Al_2O_3$: 35–60%) reflect a strong dependence on nanoparticle loading and encapsulation configuration—a variability that is itself informative about implementation sensitivity. Data: [2], [5], [6], [8], [9], [46], [47], [50]*

***Economic Barriers.*** The production cost of PCMs, as well as the cost of the nano-additives used, has to be decreased in order to allow large-scale production of PCMs and the widespread use of PCM-containing building products for new building projects.

- The cost of using nanoparticles (e.g. graphene and other materials) mixed with PCMs in building projects (mainly residential) is too expensive to use in building.
- PCMs, as well as the required nano-materials, are imported, so there are no local production lines for building materials containing PCMs
- Market Awareness: PCM technology is still emerging in regional construction markets, and therefore, there is a lack of awareness amongst builders and developers.

**Practical Challenges.**

- Lack of Long-Term Field Studies: The majority of studies that have been experimental in nature have been conducted in laboratories within the region. These studies lack long-term in-situ performance data for PCM-containing building products under a variety of environmental conditions.
- Lack of Guidelines to Integrate PCMs in Building Codes for Design and Construction of Buildings.
- If a leakage occurs, the integrity of the encapsulation has to be checked and maintained.

PCM has to be recognized by the energy policies of Iraq and the Gulf region as a strategic energy-efficiency measure.

- Absence of regulatory frameworks which include introducing PCM in building retrofitting in order to increase energy efficiency with incentives.
- The lack of governmental funding for PCM-related research and pilot projects in Iraq and neighboring countries.
- PCMs in buildings are not included in sustainability programs in Iraq and green building certification schemes in Iraq and the Gulf region in order to enhance energy efficiency and conserve energy, as shown in Figure 3.

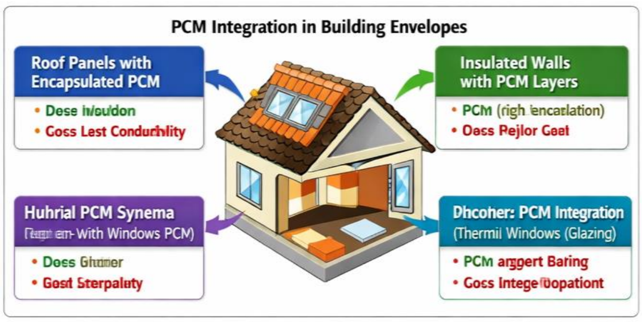


*Fig. 3. Schematic illustration of PCM integration in building envelopes*

**Future Directions and Recommendations**

***Development of Local PCM***. To reduce dependency on imported materials and lower costs, Iraq and neighboring Gulf countries should invest in developing indigenous PCM formulations.

- Research and Innovation: Establish national research programs focused on refining local paraffin and exploring bio-based PCM alternatives derived from regional resources.

- Local Manufacturing: Create PCM production facilities to support domestic construction markets and reduce import costs.
- Material Optimization: Conduct comparative studies on Iraqi paraffin blends to tailor melting points and stability for regional climate conditions.

7.2 Pilot Projects and Demonstrations

Real-world validation is essential for scaling PCM adoption.

- Pilot Buildings: Implement PCM-integrated retrofits in residential and commercial buildings in Baghdad, Riyadh, and Dubai.
- Performance Monitoring: Collect long-term data on energy savings, comfort levels, and material durability under actual climatic conditions.
- Knowledge Dissemination: Showcase successful case studies to promote awareness among architects, engineers, and policymakers.

***Integration with Renewable Energy.*** PCM can complement renewable energy systems to enhance sustainability.

- Solar-PCM Hybrid Systems: Combine PCM with solar PV and solar thermal collectors to store excess heat and improve cooling efficiency.
- Off-Grid Applications: Develop PCM-based cooling systems powered by solar energy for remote or rural areas.
- Smart Control Integration: Use sensors and automation to optimize PCM charging/discharging cycles in hybrid solar-PCM systems.

The experimental work by K.A.D.Y.T. Kahandawa Arachchi et al. [51] The study addressed the incorporation of organic and inorganic PCMs into concrete. The study showed that inorganic PCMs are superior to organic PCMs, as they preserve the mechanical properties of the concrete and enhance workability. Inorganic PCMs also improved the thermal resistance of the concrete. The study showed that heat transfer was delayed by about 9%, and the peak temperature was reduced. Mohammed El Hadi Attia et al. [52] Bio-based eutectic PCMs have recently been introduced as an innovative sustainable option for TES. Bio-based eutectic PCMs are able to store energy at a wide of operating temperatures and also PCMs in eutectic mixture are able to reach high energy density values, which are favorable for low- and medium-temperature applications. In this contribution, bio-based eutectic PCMs are applied for TES at a structural scale and the results are compared with the results of the material-optimized PCMs presented by Xinye Jiang and co-workers recently in a previous work. [53], Recently, encapsulated ternary eutectic PCMs have been investigated for use in asphalt pavement. These PCMs have a high latent heat of fusion on a weight basis (up to 212 J/g) as well as good thermal properties. The use of encapsulation in the form of expanded graphite provides high thermal conductivity as well as the advantage of the leakage of the PCM from the encapsulation being prevented. Recently, a review of PCMs has been published by Changlu Xu et al. [54] The low thermal conductivity of PCMs is a limiting factor for their thermal performance. Here, a survey of PCM enhancement by incorporating carbon- and metal-based additives is given. This article provides the theoretical background for the results presented in several applied studies such as Jiang et al. [53].

Further advancing PCM engineering for building applications, Yuanjun Yang et al. [55] We design binary eutectic hydrated salt composites to have supercooling, improved phase stability and encapsulation, for prolonged thermal storage and improved thermal storage efficiency in building envelopes. Zhongtian Zhang et al. [56] We investigate the use of organic/inorganic composite PCMs for cold thermal energy storage. Additives modify hydrogen bonding and molecular interactions between molecules. In PCMs this leads to a decrease in melting temperature, a decrease in supercooling and an increase in storage life. We combine experiments with Molecular Dynamics simulations.

***Policy and Incentives.*** Governmental support is crucial for mainstream adoption.

- Financial Incentives: Offer tax credits, grants and/or low-interest loans to retrofit homes with PCMs and to build energy-efficient homes as depicted in Figure 4.
- Establish national guidelines for the inclusion of PCMs in building codes and in sustainable building certifications.
- Education and Training: Support professional development programs to train engineers and architects in PCM design and implementation.

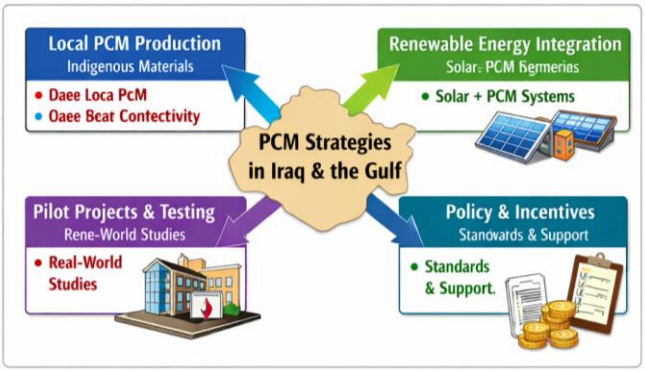


*Fig. 4. Framework of PCM development strategies in Iraq and the Gulf*

**Conclusion.** The review will start from the application of PCM in buildings to enhance energy efficiency and thermal comfort in hot climate regions. Encapsulating PCM into composite materials (e.g. building materials containing PCM) in the form of paraffin or nano-enhanced PCM is a method to use PCMs efficiently in hot-arid climates for building applications. In these climates, using locally made Iraqi paraffin PCM can reduce the cooling load by 20%–30% and is cost effective. Moreover, the conductivity of nano-enhanced PCM can be increased up to 60% by using $Al_2O_3$, $TiO_2$ and graphene etc. The related reduction of cooling load is between 35%–60%. Utilizing hybrid PCM systems (e.g. PCM-embedded radiant ceiling and capillary tube networks) can not only enhance thermal comfort and also can reduce peak cooling loads up to 40%. Integrating PCMs with passive building concepts (e.g. shading, high- performance insulation and optimal glazing-PCM integration) can save energy in cooling up to 70%.

However, technical, economic and strategic problems have to be solved. First of all, problems of using PCMs such as leaks, instabilities and segregation of the components have to be solved. On the other hand, there are economic restrictions, mainly caused by high prices of nanoparticles and the lack of producers of PCM in Iraq and the Gulf. Strategic investments in PCM production on the Iraqi market are necessary. The biggest problem is lack of national building regulations as well as political support.

This paper provides suggestions to improve the use of PCMs in very hot climates such as Iraq and the Gulf.

1. Local PCM materials have to be developed by using paraffin or bio-based materials which are locally available.
2. Testing of PCM in pilot buildings, especially in residential buildings, as well as in commercial buildings, in order to test its efficiency.
3. PCM hybrid cooling system that is integrated with renewable energy systems such as solar PV and solar thermal collectors.
4. Establish national standards and to create an environment that encourages the implementation of PCM within sustainable building.

PCM can be transformed into innovative building elements for building in the Middle East. By further developing the PCM on the basis of locally available paraffin or bio materials and by improved PCM-encapsulations or -composites, by developing building elements using PCM and by the implementation of PCM into holistic building concepts, new possibilities for energy-efficient building designs in hot climate regions are opened up. This could decrease the specific cooling energy demand, increase user comfort and support sustainable urban development.

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